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**Final Report Submitted to  
the National Aeronautics and Space Administration  
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Entitled:**

**VARIATION OF THE SOLAR LYMAN- $\alpha$  LINE PROFILE  
WITH SOLAR ACTIVITY**

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## Scientific Background

The disk-averaged solar Ly- $\alpha$  line profile shape has been determined during quiet solar conditions from center and limb spectra by Lemaire et al. (1978) and Fontenla, Reichmann, and Tandberg-Hanssen (1988). It is well known that the integrated solar Ly- $\alpha$  flux varies with solar activity. This variation occurs both over the 11-year solar cycle as well as over a solar rotation as active regions pass on the visible face of the sun. The solar line profile shows a self-absorption at the center; but there has been considerable controversy over whether the shape of the line (i.e. the depth of the central absorption) changes in proportion to the integrated flux. The full-width at half-maximum for the solar line is about 0.8Å.

Understanding the variation of the shape of the Ly- $\alpha$  line profile is not only important and interesting from the standpoint of solar physics, it is also important for understanding observations of H Ly- $\alpha$  from various solar system objects. Most of the interest is in interpreting observations of resonance scattering of solar Ly- $\alpha$  radiation by hydrogen atoms in various atmospheres. Most planetary atmospheres which scatter Ly  $\alpha$  are nearly at the center of the self-absorbed solar line, so knowledge of the variation of the solar line-center flux would be very useful. Such measurements would also be useful for separating the effects of resonance scattering as opposed to auroral emissions in the giant planets (Clarke et al. 1989; McGrath and Clarke 1991). Comets, on the other hand, are in highly elliptical orbits and therefore can "move" from line center to Doppler shifts as large as  $\pm 50$ -60 km/s (Combi and Smyth 1988, Combi and Feldman 1992).

Direct solar observations have indicated that the line-center flux may vary more than the integrated flux based on a reconstruction of a full solar disk spectrum from a number of smaller scale observations (Lean 1987). However, years of spacecraft observations of the interstellar medium both by Pioneer Venus (Ajello et al. 1987) and Voyager (Shemansky and Judge 1982; Shemansky 1991) are consistent with little or no variation of the ratio of the line-center to integrated flux.

The objective of this program was to use IUE to observe the shape of the solar H Ly- $\alpha$  line profile as reflected by the Moon and its variation (if any) with changes in solar activity. One goal was to determine any changes in the shape of the line with the variation in solar activity during a few solar rotations. Another long term goal was to measure the line profile first during this epoch, just after solar max, and monitor any changes in the line shape, in particular in the relative level of the self-absorbed line center, with long-term changes in solar activity.

**Observations of Solar Lyman- $\alpha$  Reflected by the Moon** Eight observations were made covering years 15, 16, and 17. During year 15 (the full IUE year) four US2 shifts were awarded, mainly to demonstrate feasibility. During years 16 and 17 two US1 shifts were awarded. All spectra were taken with the short-wavelength small aperture (SWSA) with the large aperture closed. All were taken such as to maximize the integration time during the 8-hour shifts. Table 1 gives a summary of relevant data concerning the spectra.

**Table 1. IUE High Resolution Solar Ly- $\alpha$  Spectra**

	Date	DOY	Spectrum	Shift	F10.7
1	11/13/92	319	SWP46264	US2	126
2	1/13/93	14	SWP46724	US2	133
3	2/3/93	35	SWP46884	US2	147
4	3/4/93	36	SWP47093	US2	160
5	12/22/93	357	SWP49673	US1	105
6	12/23/93	358	SWP49678	US1	111
7	8/17/94	230	SWP51843	US1	77
8	10/15/94	289	SWP52418	US1	91

DOY - Day of Year

F10.7 - the F10.7 flux: serves as an indicator of solar activity and Ly- $\alpha$  flux

A number of difficulties presented themselves in the course of this work. During the first four US2 shifts background radiation noise was a problem, albeit expected to some degree. The other problem was that of guiding on the moon. At the beginning of the effort, we obtained a lunar ephemeris program from colleagues and past IUE lunar observers D. Hall and D. Shemansky. In our experience with it, it seemed that the program accurately provided the position of the moon at given times (i.e., right ascension and declination), however the tracking corrections seemed to not be accurate. The success of the use of the tables was in the final analysis spotty. Our attempts and those of the IUE observing staff failed to find the error in the code.

However, by this past year, the telescope operators and resident assistants devised a method to use FES images for guiding which in the final analysis proved quite good. Table 2 provides a list of the qualitative assessment of the IUE spectra of the moon.

**Table 2. Quality Analysis of IUE High Resolution Solar Ly- $\alpha$  Spectra**

Spectrum	Quality	Commentary
SWP46264	Poor	High Noise, Moderate Signal
SWP46724	Poor	High Noise, Poor Guiding
SWP46884	Poor	High Noise, Poor Guiding
SWP47093	Good	Low Noise, High Signal
SWP49673	Poor	Low Noise, Poor Guiding
SWP49678	Poor	Low Noise, Poor Guiding
SWP51843	Good	Low Noise, High Signal
SWP52418	Good	Low Noise, High Signal

In the end we are left with 3 out of the 8 spectra being useful and of high quality. SWP47093 was taken during a relatively radiationally quiet US2 shift on March 3, 1993, when the F10.7 flux of 160 indicated that the solar activity was the highest of the eight days of observations. SWP51843 was taken on August 17, 1994 when the F10.7 flux was 91. SWP51418 was taken on October 15, 1994 when the F10.7 flux was 77, its lowest of all the observations. Since the solar activity was similarly low for the last two spectra we have summed them to further reduce the noise compared with the signal. The resulting line profiles are shown in Figures 1 and 2. The factor of 1.9 in the ratio between the active and quiet F10.7 fluxes implies a corresponding ratio of about 1.3 in the solar Ly- $\alpha$  flux.

Figure 2 is quite similar to the quiet-sun disk-integrated solar Lyman- $\alpha$  line profile constructed by Lemaire et al. (1978) from high-resolution disk-centered and limb spectra, and the more recent quiet-sun average profiles shown by Fontenla, Reichmann, and Tandberg-Hanssen (1988). The Lemaire et al. profile, as digitized and used in comet coma modeling by Combi and Smyth (1988), is shown in Figure 3. The overall structure

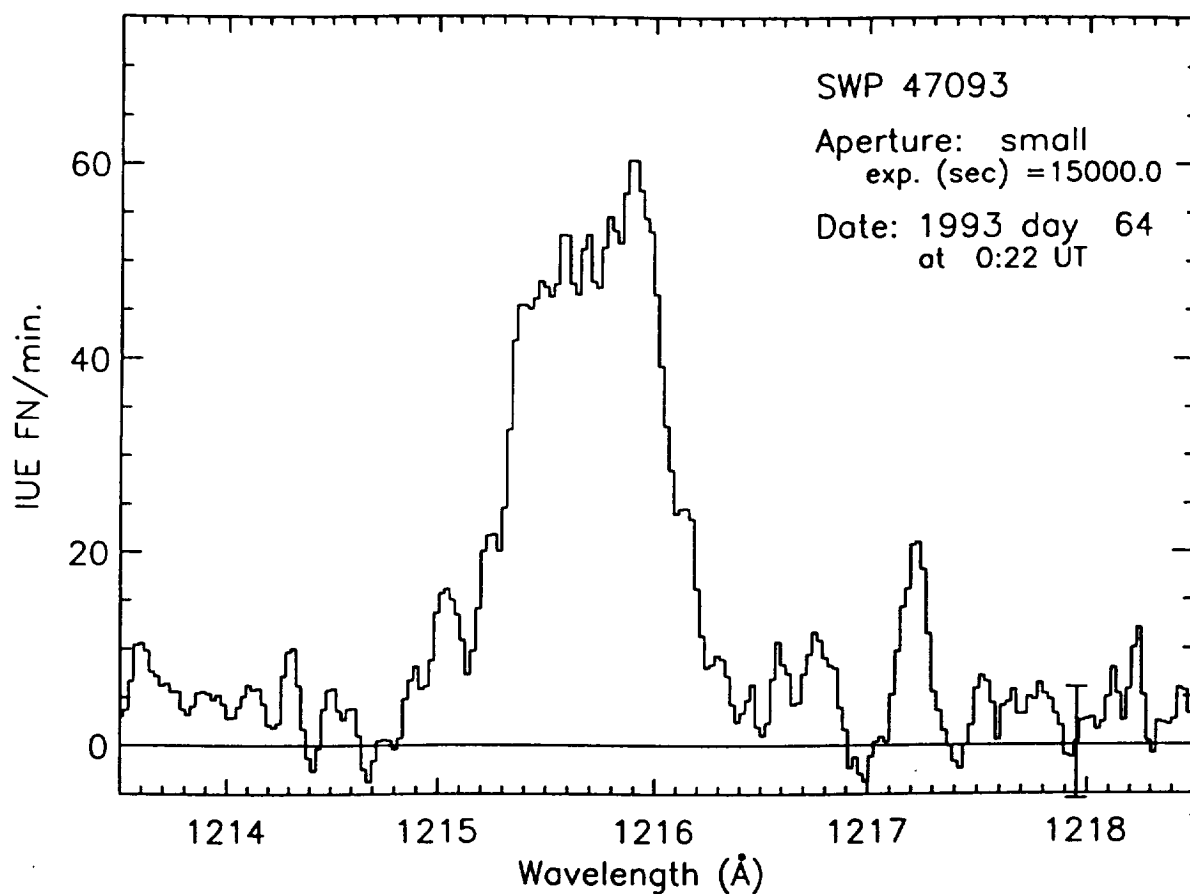


Figure 1. IUE SWSA Spectrum of the Solar Lyman  $\alpha$  line, reflected from the moon, is shown. This exposure was taken during a US2 shift in March of 1993 and at the largest level of solar activity (and corresponding solar Lyman- $\alpha$  line flux). The line shape is quite different from the quiet-sun profile however the depth of the central reversal, and the line-center flux are not well determined because of the uncertain geocorona level.

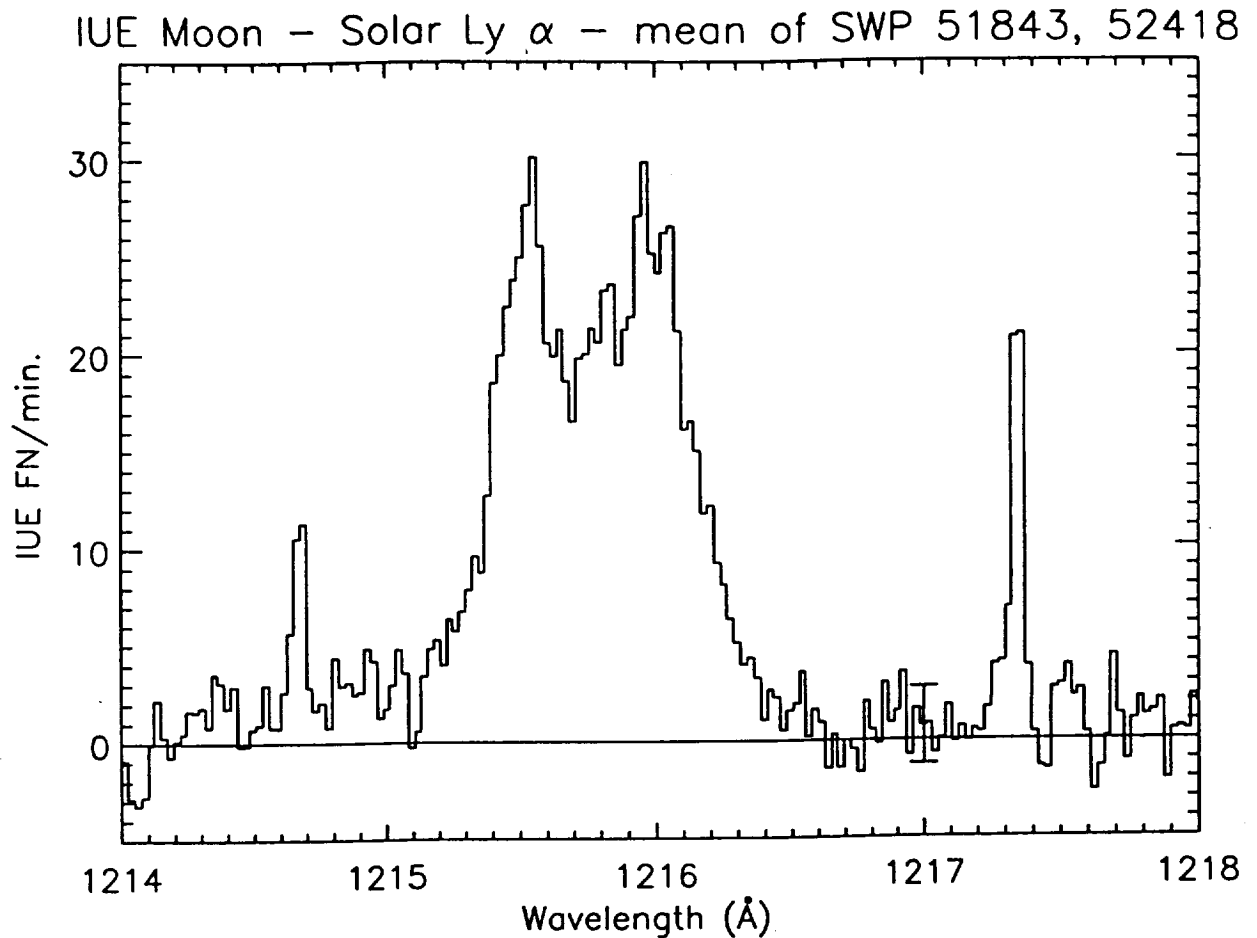


Figure 2. IUE SWSA Spectrum of the Solar Lyman  $\alpha$  line, reflected from the moon, is shown. This exposure is a composite of two spectra taken during US1 shifts in August and October of 1994 and at the lowest level of solar activity (and corresponding solar Lyman  $\alpha$  line flux). The line shape is similar to various published quiet-sun profile, however the depth of the central reversal, and the line-center flux are not well determined because of the uncertain geocorona level. There is an indication of a contribution of geocorona at the line center.

is the same with the left peak being a bit higher than the right, and also to the more recent data of Fontenla, Reichmann, and Tandberg-Hanssen. The contribution of the geocorona is quite clearly present in Figure 2 as the small emission peak near the bottom of the self-reversed solar line profile. The other profiles are made looking directly at the sun so the geocorona is actually seen in absorption and had to be filled back in by appropriate data analysis.

The active-sun IUE profile from March 1993 on the other hand appears quite different from the quiet-sun ones. In this one the right side peak (long wavelength) is higher than the left and the central portion of the line is more "filled-in" compared with the quiet-sun profiles. Unfortunately, since the shape of the geocorona contribution to the solar line is not plainly distinct in either spectrum it cannot be adequately removed. Furthermore, since we cannot be sure of the relative levels of the reflected lunar and geocoronal contributions (because of guiding and unknown variations in lunar albedo), we cannot say with certainty that the center of the active-sun profile is more filled-in compared with the quiet-sun. It is clear, however, that the shape of the line has changed, and there is an suggestion that the central reversal is more "filled-in" at the higher flux (solar activity) level..

This type of difference is quite similar to those shown by Fontenla, Reichmann, and Tandberg-Hanssen (1988) in their spectra of various small areas, active and quiet, at various locations on the disk sun. Therefore, we believe the IUE spectra obtained to date clearly indicate that the shape of the disk-averaged Ly- $\alpha$  line profile does vary with solar activity, i.e. with changes in the integrated Ly- $\alpha$  flux of 30%. However, because of the various complications, we cannot yet quantitatively characterize the details in the variation, such as the depth of the central line reversal. Finally, we believe that our observations to this point demonstrate that IUE has the capability, with a somewhat revised procedure on our part, to make quality measurements of the line profile shape. If IUE continues to be operated over the next few years we can in principal measure the solar Ly- $\alpha$  line profile as the solar activity level increases from the current solar minimum condition.

### **The Future: Continued IUE Observations**

We are considering requesting further IUE observing time to continue this program in a more systematic way despite the lack of future funding. The measurements have and can continue to be made as service observations. Now that the IUE staff has developed a successful method for tracking the moon during a long exposure using the FES, we are



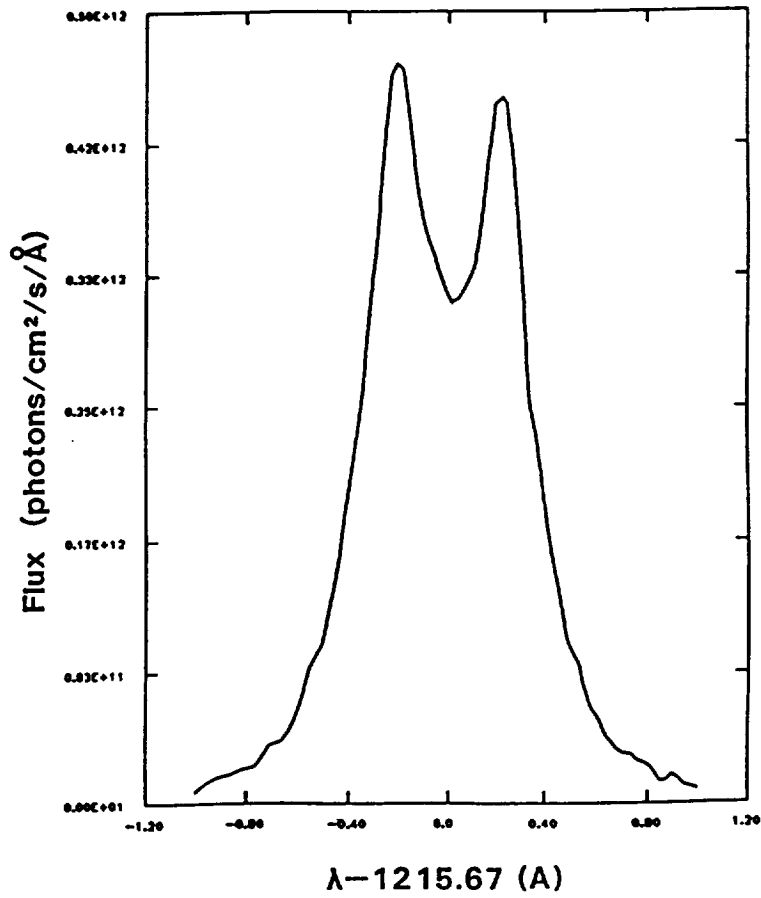


Figure 3. The Quiet-Sun Lyman- $\alpha$  Line Profile. Shown is the Lyman- $\alpha$  line profile constructed by Lemaire et al. (1978) from disk-center and limb spectra. The data are shown here from a digitized version used in a cometary Lyman  $\alpha$  coma model by Combi and Smyth (1988).

planning to request sets of three successive days of US1 shifts, at the optimal times with respect to the full moon in August and October. A SWSA spectrum of the moon would be taken during the second US1 shift as we have obtained recently. The first and third shifts would be used to measure the geocorona flux from the same region of the sky (i.e. the same line-of-sight and time of day) as the moon spectrum. Daily averages of the integrated solar Lyman- $\alpha$  can for the present be obtained from the SOLSTICE and SUSIM instruments which are active on the UARS (Upper Atmosphere Research Satellite). In this way the known geocorona flux can be convolved with the SWSA point-spread-function and the properly calibrated geocorona profile can be subtracted from the moon-reflected solar profile.

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